

Magnetically and thermally modulated microwave absorption in $Y_1Ba_2Cu_3O_{7-x}$ single crystal near T_c

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Abstract

The microwave absorption R in the $Y_1Ba_2Cu_3O_{7-x}$ single crystals was investigated near $T_c \approx 92K$ and in the external magnetic field $0 < H \leq 9kOe$ kOe. A modified ESR spectrometer was used in the experiment. The method of temperature modulation, along with the usual method of magnetic-field modulation, was first applied in studying of the microwave response of these crystals. Peaks in the temperature dependencies of the signals $\partial R/\partial H$ and $\partial R/\partial T$ observed in the vicinity of T_c were differently shaped and slightly shifted one with respect to another. The evolution of the peaks with variation of the magnetic field and angle θ between \mathbf{H} and the \mathbf{c} -axis was traced. It has been shown that the observed difference of the temperature dependencies of the derivatives $\partial R/\partial H$ and $\partial R/\partial T$ occurs due to the field-induced broadening of the superconducting transition, which is inherent in the high- T_c superconductors.

Keywords: Temperature modulation; Magnetic-field modulation; Superconducting transition; Microwave absorption; High- T_c superconductor

1 Introduction

It is well known that the superconducting transition in the high- T_c superconductors shows a dramatic [1] field-induced broadening. In particular this phenomenon prevents from determining the upper critical field $H_{c_2}(T)$ for high T_c superconductors by traditional methods. The origin of the broadening is still unclear and remains a subject of investigations [2] - [10].

As a source of information on superconducting transition properties the results of microwave measurements performed by technique of ESR spectrometers may be useful. It has been found [11] - [15] that temperature dependence of the microwave response of high- T_c superconductors, recorded by an ESR spectrometer with modulating magnetic field, exhibits a peak near T_c . It should be noted that in this case the measured signal represents the

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derivative $\partial R/\partial H$, where R is a microwave absorption. In this connection it has been supposed [12, 14] that the temperature dependence of $\partial R/\partial H$ in the vicinity of T_c is similar to that of $\partial R/\partial T$, as it occurs for traditional superconductors, and so the observed $\partial R/\partial H$ -peak may be used for analysis of superconducting transition in the high- T_c superconductors.

An original point of the present paper is that we have fulfilled the direct measurement of the derivative $\partial R/\partial T$ for a single crystal Y-Ba-Cu-O and established the essential difference of its temperature dependence from that of the derivative $\partial R/\partial H$. It is shown that this difference is due to the field-induced broadening of superconducting transition.

2 Experimental

In the experiment the ESR spectrometer SE/X-2543 "Radiopan" with the X-band TE_{102} resonant cavity ($\nu = 9.5GHz$, $Q = 5000$) was employed.

A usual field arrangement with $\mathbf{H} \perp \mathbf{H}_1$, where \mathbf{H} is the static field and \mathbf{H}_1 - the microwave field was used (see insert in fig. 2). The crystals were oriented with $\mathbf{c} \perp \mathbf{H}_1$. The angle θ between the \mathbf{c} and \mathbf{H} could be varied by rotating the crystal around the \mathbf{H}_1 direction and could be fixed with an accuracy of $\pm 1^\circ$.

In order to investigate the superconducting transition at low fields some modifications are made because the electromagnet of ESR spectrometer has remnant magnetic field with $\sim 30Oe$. The resonator is taken out from the large electromagnet and for creating low fields a pair of Helmholtz coils is used. To ensure that the field is zero at the zero current in the coils, the resonator and coils were placed inside the cylindrical permalloy screen, reducing the geomagnetic field more than hundred times.

A light-beam assisted temperature-control system operating within a temperature range from 77 to 180 K was specially designed for this experiment [16]. The advantage of this system is the feasibility of modulating the temperature of a sample with a frequency of 80 Hz and amplitude of $10^{-2} - 10^{-1}$ K. The rms temperature instability over a 5-min time interval is within 0.06 K, the temperature gradient in a sample is - 0.01 K/mm for $T \sim 90$ K, and system relaxation time is 1-10 s.

The lock-in detection was used for recording the modulated microwave absorption for the following cases:

- a) at frequency 100 kHz when modulating magnetic field was applied (maximum modulation amplitude $h_{max} = 10$ Oe),

- b) at frequency 80 Hz in the case of modulating the temperature of a sample.

It should be noted that a direct measurement of the temperature modulation amplitude represents a rather complicated problem. Here we can point that, according to ref. [16], its value can be chosen in the range $10^{-2} - 10^{-1} K$, and that its variation over the transition region does not exceed 10%. Since the amplitude is much less than the transition width, the observed signal can be considered as the derivative $\partial R/\partial T$.

All the measurements were carried out at the constant microwave power level of -17 dB (130 mW).

The single crystals were grown from the melt $Y_{0,99}Ba_{2,00}Cu_{2,89}O_{7-x}$. The mixture was heated to $1100^{\circ}C$ in the $ZrO_2 : Y$ crucible at the rate $2 - 5^{\circ}C/h$, and then cooled to the room temperature at the same rate. The crystal composition was determined by the method of X-ray micro-spectroscopy and corresponded to the formula $Y_{0,99}Ba_{2,00}Cu_{2,89}O_{7-x}$. The lattice parameters, as determined by the X-ray diffraction, were: $a = 3,85\text{\AA}$, $b = 3,89\text{\AA}$ and $c = 11,74\text{\AA}$. The crystals were shaped as thin plates with thickness $d \sim 0,03mm$ along the **c** and area of $< 1mm^2$ in the (**a**, **b**) plane.

3 Experimental results and discussion

The crystal samples exhibiting simple-shaped single peak in the temperature dependence of the derivatives $\partial R/\partial H$ and $\partial R/\partial T$ were selected for detailed studies. The so called "low-field" signals [17, 18] were absent in all samples. These conditions ensured that the observed temperature dependence of the measured signal was determined exclusively by the superconducting transition. It should be stressed also, that no irreversible effects were observed in the studied samples.

In general 5 samples were investigated. All the results obtained in the experiment might be summarized in several regularities demonstrated in figs. 1-3 (all figures refer to the same sample). The most important result is the qualitative difference of the temperature dependencies of the derivatives $\partial R/\partial H$ and $\partial R/\partial T$. It is seen in fig. 1, that the corresponding peaks are shifted one with respect to another in the temperature scale. Moreover, the $\partial R/\partial H$ peak is broader than the $\partial R/\partial T$ peak and has an asymmetric shape with a clearly seen low temperature tail. A different behavior of these peaks with increasing external field is also seen in fig. 1. The amplitude of the

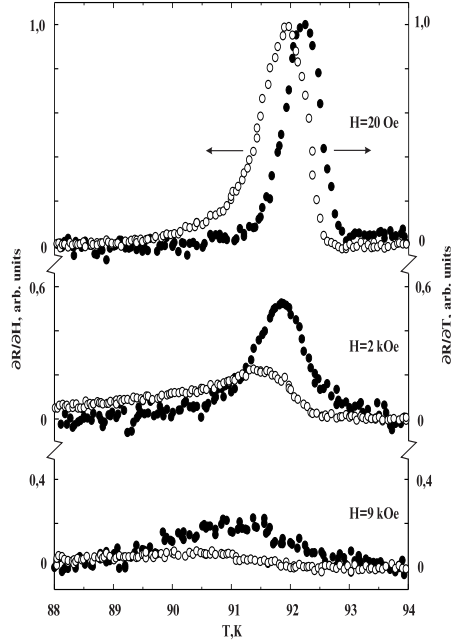


Fig.1. Temperature dependencies of the derivatives $\partial R/\partial H$ and $\partial R/\partial T$ at $\theta = 0$ and different H .

$\partial R/\partial H$ peak decreases faster than that of the $\partial R/\partial T$ one, and shows a larger shift toward lower temperature.

We have also studied an asymptotic behavior with the decreasing external field, $H \rightarrow 0$. It was found that below 20 Oe the amplitude and position of the $\partial R/\partial H$ peak remain constant, in the range of error limits, and its shape became more symmetrical with decreasing field, approaching that of the $\partial R/\partial T$ peak. The latter did not experience any changes down to the lowest attainable field strength of $10^{-3} \div 10^{-2}$ Oe.

Measurements of the derivative $\partial R/\partial H$ at $H \rightarrow 0$ are subject to a specific problem. The corresponding ΔR signal was recorded at the values of field modulation amplitude h compatible with the condition $\Delta R \sim (\partial R/\partial H) \cdot h$. Special tests showed that this condition fulfilled as long as $h < H$. The latter condition made it difficult to carry out measurements at $H < 2,5 \text{ Oe}$, and at $H = 1 \text{ Oe}$ the ΔR signal fell to the noise level. This should be kept in mind when considering our conclusion about the constancy of the $\partial R/\partial H$ peak amplitude and position at $H \rightarrow 0$.

The $\partial R/\partial H$ and $\partial R/\partial T$ peaks differently responded to the variation of the angle θ from 0° to 90° .

At low fields, $H \leq 20 \text{ Oe}$, the $\partial R/\partial T$ peak was practically constant in the range $0^\circ \leq \theta \leq 90^\circ$, whereas a significant changes of the $\partial R/\partial H$ peak

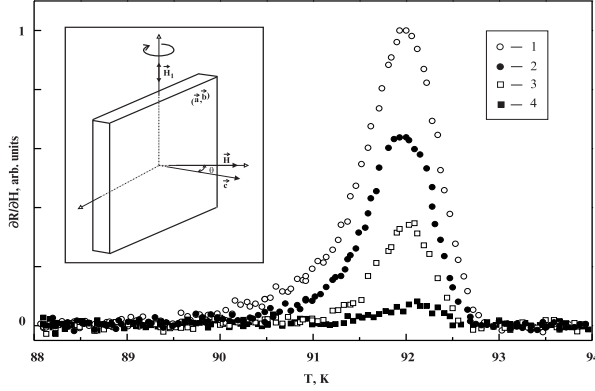


Fig.2. Evolution of the temperature dependence of the derivative $\partial R/\partial H$ at $H = 20$ Oe with changing angle θ . The geometrical arrangement of the experiment is shown in the insert.

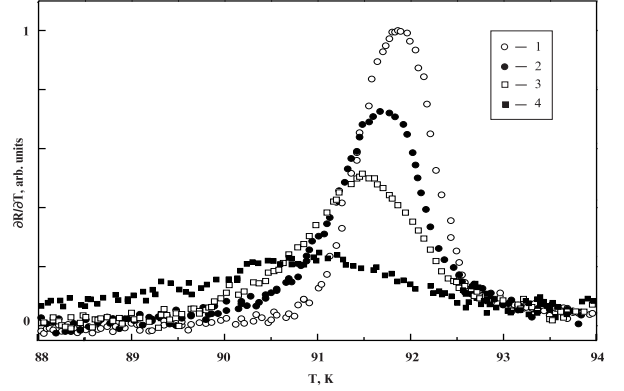


Fig.3. Evolution of the temperature dependence of the derivative $\partial R/\partial T$ at $H = 9$ kOe with changing angle θ .

features were observed. The amplitude of $\partial R/\partial H$ peak decreased gradually, reaching at $\theta = 90^\circ$ about 1/10 of its initial value, while its position shifted slightly toward higher temperature (see fig. 2). At high fields these peaks showed a reverse behavior: the $\partial R/\partial T$ peak changed significantly (see fig. 3), whereas the $\partial R/\partial H$ peak remains unchanged.

Common features of these two peaks were their narrowing and shifting to higher temperature (for about 1 K and 1.5 K correspondingly at $H = 9$ kOe) when increasing θ to 90° .

We preface the discussion of the results with the following remark. The absorption function $R(H, T)$ satisfies the identity:

$$\partial R/\partial T = -(dH_r(T)/dT) \cdot (\partial R/\partial H), \quad (1)$$

where $H_r(T)$ is determined by the equation

$$R(H_r(T), T) = r = \text{const.}$$

The function $H_r(T)$ describes the "equiabsorption" line in the phase plane (H, T) . Such a line in the region of the superconducting transition is commonly interpreted as the temperature dependence of the upper critical field $H_{c2}(T)$. This interpretation is valid provided that the dependence of the line's slope dH_r/dT on the absorption level r is weak in the temperature interval of the transition at any values of H (otherwise, the lines $H_r(T)$ with different

r would diverge in the phase plane, and choosing of $H_r(T)$ for $H_{c2}(T)$ would be uncertain). Usually, this condition is fulfilled in the low-temperature superconductors and in this case, according to eq.(1), the temperature dependencies of $\partial R/\partial H$ and $\partial R/\partial T$ have to be similar. Note, that this is possible only if the curve $R(H = \text{const}, T)$, describing the superconducting transition, is shifted as a whole with changing field H .

It is seen in fig.1 that the peaks in the temperature dependencies of the derivatives $\partial R/\partial H$ and $\partial R/\partial T$, for a given high- T_c superconductor, are differently shaped, and, which is more important, are shifted one with respect to another in the temperature scale. This means, according to eq. (1), that the value of dH_r/dT is not uniform in the transition region and therefore should be essentially dependent on the absorption level. Hence, the relative shift of the peaks seen in the graphs of fig.1 is an evidence of the field-induced broadening of the superconducting transition. It should be underlined also, that the comparative analysis of the peaks $\partial R/\partial H$ and $\partial R/\partial T$ allows one to observe the transition's broadening even at very low fields. A direct observation of this effect would require a much higher precision of temperature measurements. Thus, we hope that the results described above may be used in testing the existing models of the field-induced broadening in high- T_c superconductors.

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